Induced Technological Change: The Timing of Abatement and the Impact of Internalizing R&D Externalities in the BAU

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Abstract

The economic modelling community has put great effort into incorporating endogenous technological change into their models; however, there is little consistency in the modeling of the business-as-usual scenario. This paper examines the impact of research and development externalities often included when considering induced technological change. These externalities should remain external to the representative agent. The optimal timing of abatement remains up for debate and the externalities internalized by the representative agent will affect the implied scale and timing effects of induced technological change. We follow the model of Shiell and Lyssenko (2014). We incorporate Gerlagh's price deflator to normalize shadow values and to allow us to follow Mercenier and Michel (1994a, 1994b) in applying varying time periods. The model is solved for eight scenarios with various combinations of research and development externalities internalized in the business-as-usual. Without any externalities internalized by the representative agent, induced technological change is responsible for less than 20% of optimal abatement. That share of abatement appears higher with duplication and crowding out, and lower with leakage externalities internalized. We find evidence that induced technological change delays abatement, and that internalizing duplication and crowding out externalities exaggerates the delay while, while internalizing leakages negates it.

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Introduction

Controlling climate change is one of the world's greatest challenges and sources of discussion in academics. The potential damages from greenhouse gas pollution are enormous; of that there is little argument. A plan of action is critical both domestically and internationally. Coming to an agreement on policies is no small task, as there will inevitably be trade-offs. Forming an opinion on policy is often dictated by the assumptions made, especially when we are informed by economic models. The models are by definition stylized representations of reality and it is imperative that they are constructed to accommodate the question at hand, without becoming too cumbersome. A key ingredient in modern energy-economy modelling is endogenous technological change (ETC). The economic modelling community has put great effort recently into incorporating this aspect of reality; however, the appropriate specification remains unclear. There are many highly detailed, quality reviews of this literature, and we will only discuss it briefly. Our focus is the debate over the optimal timing of greenhouse gas (GHG) abatement and the impact of research and development (R&D) externalities often included when incorporating ETC into a model. These externalities ought to be external to the representative agent (RA), and internalized only in the optimal scenario, not in the business-as-usual (BAU) scenario[1]. This is often not the case in the literature, and we explore the impact internalizing these externalities in the BAU has on the implied impact of induced technological change (ITC)[2]. The impact of ITC on the scale and delay in abatement is modest, but will be inflated by internalizing duplication and crowding out externalities and deflated by internalizing inter-firm leakages.

Clark and Weyant (2002), Edenhofer, Lessmann, Kemfert, Grubb, and Köhler (2006), Gillingham, Newell, and Pizer (2008), and Köhler, Grubb, Popp, and Edenhofer (2006), among others, provide extensive background on endogenous growth modelling, ETC, and ITC. Technology was first introduced exogenously. Top-down models relied on assumptions on the elasticity of substitution between carbon and non-carbon inputs, while bottom-up models contained more detailed representations of technology, but nonetheless relied on assumptions surrounding future energy and technology. In time, top-down models began to incorporate both

[1] Optimal here does not necessarily mean first-best, and second-best scenarios may also internalize the externalities.
[2] ETC is used to describe technological change which has been incorporated into the model. ITC is the result of policy which induces additional technological change, possible through ETC.

R&D accumulation and learning-by-doing (LbD) (Grubb et al., 2006). R&D is often referred to as "learning-by-searching", the intertemporal aspect of which is referred to as "standing on shoulders" because past research makes discovering technologies in the future cheaper. LbD on the other hand implies that past technology use (abatement) makes discovering future technologies cheaper. Initially this may seem like a small difference, but the implication is great. With R&D accumulation, new technology lowers abatement costs without needing to be implemented (only the knowledge development is required), thereby allowing delayed abatement. In contrast, LbD requires abatement in early periods in order to impact the costs of future abatement. Which of the two knowledge specifications is used will clearly play a large role in the timing implications of a model.

Gerlagh, Kverndokk, and Rosendahl (2009) concisely summarize some arguments in favor of both delayed and accelerated abatement. Discounting implies that later abatement can be greater at equal net present costs, while the "natural depreciation" of GHGs in the atmosphere means that total emissions can be higher by shifting emissions to the present. Also, in the future there will likely be cheaper abatement options than those available today. However, if we believe that technologies must be used before they can lower abatement costs (LbD), then we need to accelerate abatement. Another common argument for action today is that capital is long-lasting and we cannot expect to switch quickly/affordably in the future.

Those first arguments for delay are made by Wigley, Richels, and Edmonds (1996). In their early and influential paper they consider the timing of abatement to be a "carbon budget allocation problem" (p. 242). They argue that the further into the future we delay, the fewer resources necessary to reach stabilization targets, and that we should commit some time to adjusting capital stocks. They also comment that while low-carbon technologies will become available in the future, that does not imply that we should do nothing, a point echoed by Grübler and Messner (1998). They incorporate ETC and agree with Wigley et al. (1996) that short-term abatement is unlikely/non-optimal, but emphasize the near-term as a time for investment in R&D rather than general inaction. Grübler and Messner (1998) also emphasize the role of a high discount rate in arguments for delay.

Ha-Duong, Grubb, and Hourcade (1997) and Jaccard and Rivers (2007) focus on the implications of capital turnover. Even excluding LbD, not-doing implies that capital stocks are dirtier, from which future deviations will be costly. With early policies, long-lived capital can be replaced in time to hit targets without premature retirement. They both are essentially emphasizing the “inertia”, in the words of Ha-Duong et al. (1997), of economic systems, and that early policy sends the appropriate signal that clean capital should replace dirty capital as it is retired. Jaccard and Rivers (2007) also comment briefly on irreversibilities and uncertainty of climate damages, referencing Pindyck (2000, 2002) and Kolstad (1996a, 1996b).

As noted above, the intertemporal externality associated with R&D has implications for timing results; furthermore, the research market itself is characterized by externalities. The literature on these distortions has blossomed in recent years, see Buonanno, Carraro, and Galeotti (2003), Goulder and Schneider (1999), Köhler et al. (2006), Popp (2010). The social return on research investment is much greater than the private return (Nordhaus, 2002), and R&D investment is less than one quarter of the optimal level (Jones and Williams, 1998). Jones and Williams (2000) note that leakages in the R&D market as well as the intertemporal externality promote underinvestment in R&D. Leakages are the inability of firms to capture the complete social benefit of their research. Duplication comes as a result of research spending by multiple entities on the same technology. Often called “stepping on toes”, it promotes overinvestment in R&D. It is closely related to creative destruction, which Jones and Williams (2000) discuss as well. Another common externality of the research market is crowding-out: investment into R&D in one sector at the expense of R&D spending in another sector.

Goulder and Mathai (2000) discuss both timing and externalities, but a large standout of their paper is the discussion of alternative optimization criterion. The “cost-effectiveness” criterion relates to stabilizing at a CO2 concentration at minimum cost. The “benefit-cost” criterion relies on the selection of an optimal concentration, maximizing benefits of reduced damages net of abatement costs. Under the cost-effectiveness criterion they find that an R&D specification “minutely” delays abatement, while an LbD specification shows a slight increase in initial abatement; both lower the cost considerably (30% or more). In their benefit-cost cases they find that R&D accumulation (LbD) results in initial abatement falling (rising), but very little, and long run abatement much higher due to lower costs. Manne and Richels (2004) also consider LbD and their results support the conclusions of Goulder and Mathai (2000). Their interpretation is that lower future abatement costs and incentives to abate today from LbD essentially offset. They also comment that had they included R&D externalities, the benefit from LbD would likely be diminished.

Gerlagh (2008) incorporates the intertemporal, duplication, and leakage externalities of R&D. He finds that ITC leads to earlier abatement relative to the no-ITC case, and is much more optimistic about the scale of the ITC effect than other researchers. He attributes his optimism relative to Nordhaus (2002) to having additional production input and R&D substitutability, and relative to Popp (2004) due to Popp's substitutes having "strong decreasing returns to scale in production irrespective of the R&D inputs" (p. 444). However, because Gerlagh (2008) internalizes the intertemporal and duplication externalities in his BAU, there is reason to question his optimism. He also introduces a shadow price deflator which we will discuss shortly.

Hart (2008) shows the importance of incorporating crowding-out and the potential of R&D subsidies to achieve first-best results. He distinguishes between investment in production and emission-saving technologies and discusses the impact of technology spillovers. This adds a layer of complexity to an R&D subsidy's ability to compensate for underinvestment. The result is that optimal carbon taxes will not necessarily be at Pigouvian levels, and are optimally higher (lower) if clean (dirty) technologies are relatively undersupplied. Greaker and Pade (2009) are in agreement. In addition, they show the higher optimal taxation in the presence of duplication and intertemporal externalities. Gerlagh et al. (2009) shares similarities with both, and finds that "climate-specific R&D targeting" with taxes at Pigouvian levels is optimal, while taxes are optimal above Pigouvian levels if only the tax is available.

Rezai (2011) and Rezai, Foley, and Taylor (2012) argue that diverting investments towards emission-saving technologies can raise the welfare of all generations. They note that previous literature which use a "constrained optimal path" (COPT), where the BAU simply binds the RA to 0 mitigation, often come to focus on intergenerational equity, see Nordhaus (2008). In the COPT, the representative agent (RA) partially internalizes externalities. They argue when this is not the case, the intergenerational equity concern is a second-order effect, and that COPT is misleading. In a "permissible baseline solution" the RA must be aware of climate change but choose not to mitigate. By construction, COPT fails to meet the second condition.

Of course, there is also the pollution externality. In order to keep it external, Shiell and Lyssenko (2008) develop their N-agent (NA) approach. N identical sub-agents play a noncooperative dynamic game and arrive at a Nash equilibrium. The sub-agents are derived through division of the RA version of the model. As more agents are introduced the externality becomes less internalized. They show how their method can be applied to DICE 94 (Nordhaus, 1994), DICE 99 (Nordhaus and Boyer, 2000), and ENTICE (Popp, 2004). ENTICE incorporates ITC into the DICE framework. Popp (2004) finds that without ITC welfare costs are overstated by 9.4%. He also contends that estimates of a greater ITC effect on welfare in other models can be attributed to their lack of R&D externalities.

Shiell and Lyssenko (2014) “borrow heavily” from ENTICE for their model (p. 281). They examine the sensitivity of ITC results to the inclusion of R&D externalities. They support Rezai’s (2011) contention that externalities should be external in the BAU, and model it as such. They are also in agreement that the intergenerational effects of climate policy are not a primary concern. Shiell and Lyssenko (2014) find that the impact of ITC is highly dependent on the degree of duplication considered. Higher (lower) duplication shows ITC as less (more) significant. They expect duplication to be low, citing Jones and Williams (2000). Given low duplication, other externalities are significant, and R&D subsidies make first-best policy possible. We follow Shiell and Lyssenko (2014) by comparing the implied impact of ITC between scenarios in which various externalities are internalized in the BAU. We look to extract the implications that questionable BAU modelling has for the timing debate, and will also see implications for the scale of ITC’s effect.

Methodology

We use the model of Shiell and Lyssenko (2014). The model is already designed to perform analysis regarding R&D externalities, and keeps all externalities external to the RA. The model has a single region, single RA, and a single knowledge stock, used to incorporate ETC. Production and energy services are constant elasticity of substitution (CES) functions. Utility is a logarithmic function of per capita consumption and global welfare is utilitarian. The time period is 10 years and the model projects 32 periods with a rate of time preference of 0.03. Human capital dynamics are governed by R&D investment and the stock of knowledge, which does not depreciate. The human capital dynamics equation introduces the intertemporal and duplication externalities. Crowding out is incorporated into the budget constraint. Leakages play a role in both the human capital dynamics equation and the crowding out term. The climate system of

Nordhaus' (2008) DICE-2007 is used, and damages reduce net output. The social planner has both a carbon tax and a research subsidy at her disposal in order to achieve first-best policy. See Shiell and Lyssenko (2014) for a detailed description of the model.

The parameters b, φ, ℓ, and *crowdout* control the duplication, intertemporal, leakage, and crowding out externalities, respectively. We set b = 0.7, for low duplication, and $\varphi = 0$, omitting the intertemporal externality. Like Shiell and Lyssenko (2014) we set $\ell = 0.75$ and *crowdout* = 0.5. From their Table 1 we see that b = 0.7 and $\ell = 0.75$ gives the social marginal product of research (ψ) a value of 2.80. We expect this to result in the impact of leakages outweighing that of duplication; however, as noted above, duplication likely is in this lower range. Our other parameters follow their calibration, seen in their Table 2. These values correspond to those in Nordhaus (2008) and Popp (2004). As noted in Shiell and Lyssenko's (2014) Appendix, the values of ρ, α, α_F, and α_H are calibrated on a case-by-case basis to achieve an initial research expenditure (R_1) of 25 $US billion (2005), and a "research elasticity of energy R&D with respect to fossil fuel price" of 0.35 which matches Popp (2002) (Shiell & Lyssenko, 2014, Appendix). For each scenario we run, ρ and α are adjusted and α_F and α_H are calculated based on their values. The optimal scenario is run using each set of these parameters as well so as to make comparison to each BAU possible.

Table 1 outlines the scenarios run, and their unique parameters. The scenario REF keeps all R&D externalities external in the BAU, and is consistent with Shiell and Lyssenko's (2014) BAU construction (given our parameters). The scenarios L, D, and C have internalized leakages, duplication, and crowding out in the BAU, respectively. The remaining scenarios internalize combinations of externalities in the BAU, following the same naming convention.

Table 1

Scenario details

Scenario	Leakages	Duplication	Crowdout	FOCs	Altered Parameters	α	ρ
REF	No	No	No	38’, 39’	INT = 0	0.00193	-0.438
L	Yes	No	No	38’, 39’	INT = 0, ℓ = 0	0.000453	-0.457
D	No	Yes	No	27’, 29’	INT = 0	0.00283	-0.430
C	No	No	Yes	38’, 39’	INT = 1	0.00387	-0.422
LD	Yes	Yes	No	27’, 29’	INT = 0, ℓ = 0	0.000656	-0.453
LC	Yes	No	Yes	38’, 39’	INT = 1, ℓ = 0	0.00384	-0.458
DC	No	Yes	Yes	27’, 29’	INT = 1	0.00577	-0.408
LDC	Yes	Yes	Yes	27’, 29’	INT = 1, ℓ = 0	0.000553	-0.455

The column FOCs indicates which of Shiell and Lyssenko’s (2014) first-order conditions are used in the BAU. Equations (38) and (39) keep all externalities external, while (27) and (29) internalize them (typically for the social planner)[3]:

$$\Delta P_t^H (1-\ell) v_t + P_t^Y (z_t - 1) = 0 \tag{38}$$

$$P_{t+1}^H = P_t^H - P_{t+1}^E \left(\frac{EN_{t+1}}{H_{t+1}}\right)^{1-\rho} \alpha_H \tag{39}$$

$$\Delta P_t^H abR_t^{b-1} H_t^{\phi} + P_t^Y [1 + (\psi - 1) crowdout] = 0 \tag{27}$$

$$P_{t+1}^H \left[1 + a\phi R_{t+1}^b H_{t+1}^{\phi-1}\right] = P_t^H - P_{t+1}^E \left(\frac{EN_{t+1}}{H_{t+1}}\right)^{1-\rho} \alpha_H \tag{29}$$

Where Δ is the time period, v is the average product of research, z is the research subsidy (which is set to 0 in the BAU), EN is energy services, and H human capital. P^i (i = H, Y, T) represents the shadow values of human capital (knowledge), output (net of non-energy R&D), and energy services, respectively.

Our equations nearly match those in Shiell and Lyssenko (2014); although, there are a few adjustments. The ℓ term in Table 1 indicates that leakages are set to 0 rather than 0.75,

[3] As well as those shown, in Shiell and Lyssenko (2014) (37) replaces (26) in the RA’s problem, but the only notable difference is the presence of P_t^M and τ being set to 0 or not.

effectively internalizing the leakages externality in the BAU. INT is a binary parameter which is used to internalize crowding out. It is necessary to indicate its value in the table due to the changes to the above equations. In our version of the model[4]:

$$PT_t\tilde{P}_t^H(1-\ell)v_t + \tilde{P}_t^Y(z_t-1)[1+INT(\psi-1)crowdout] = 0 \tag{38'}$$

$$\beta_t\tilde{P}_{t+1}^H = \tilde{P}_t^H - \beta_t\tilde{P}_{t+1}^E\left(\frac{EN_{t+1}}{H_{t+1}}\right)^{1-\rho}\alpha_H \tag{39'}$$

$$PT_t\tilde{P}_t^H(1-\ell)abR_t^{b-1}H_t^{\phi} + \tilde{P}_t^Y[1+INT(\psi-1)crowdout] = 0 \tag{27'}$$

$$\beta_t\tilde{P}_{t+1}^H\left(1+a\phi R_t^b H_t^{\phi-1}\right) = \tilde{P}_t^H - \beta_t\tilde{P}_{t+1}^E\left(\frac{EN_{t+1}}{H_{t+1}}\right)^{1-\rho}\alpha_H \tag{29'}$$

PT_t has replaced Δ, indicating that time periods are no longer fixed at 10. Shadow values have gained tildes, and t+1 values have gained Gerlagh's (2008) price deflator (β_t).

The idea of using Gerlagh's (2008) β_t is to normalize the shadow values:

$$\beta_t = \frac{P_{t+1}^Y}{P_t^Y} = \frac{C_t/L_t}{(1+\theta)^{PT_t}C_{t+1}/L_{t+1}}$$

So multiplying all t+1 shadow values by P_{t+1}^Y/P_{t+1}^Y and dividing both sides of all first-order condition equations by P_t^Y gives the above, "normalized" versions. By normalizing the shadow values we aim to reduce the computational cost of running our scenarios. Doing so enables the extension of the time horizon and/or shortening of period lengths.

Introducing PT allows us to deviate from Shiell and Lyssenko's (2014) specification of 10 year time periods. Manne (1992) and Mercenier and Michel (1994b) examine the benefits and application of varying time periods. Although most models have uniform period lengths, it seems natural to choose shorter time periods in the short-term and longer periods as we move into the future. The ideal selection of period lengths is not so clear. Non-uniform grid spacing requires the assigning of values from t_2 up to t_{N-1}, while $t_1 = 0$ and $t_N = T$ (the terminal period). Manne

[4] Note that without the intertemporal externality ($\phi = 0$) (29') and (39') are identical.

(1992) proposes choosing their values to equalize the "utility discount factors", relying on the present value of capital. In each period the capital stock grows while its price is discounted, resulting in the curves in his figures 1 and 2. His figures 3 and 4 show the reduction in aggregation errors by using unequal time periods. Mercenier and Michel (1994b) "relate the length of time intervals to the speed of adjustment of the dynamic system to its stationary state" (p. 180). Their solution is to equalize the optimal level of net investments in each period. They come to the conclusion that the length of period n should be determined by:

$$t(n) = \frac{1}{\log(\lambda)} \log\left[1 - (1 - \lambda^T)\frac{n}{N}\right]$$

where N is the number of periods, T the time horizon, and λ is the unique stable eigenvalue:

$$\lambda = \frac{1}{2}s - \sqrt{\frac{1}{4}s^2 - (1 + \theta)}$$

$$s = 2 + \theta + \frac{1}{(1+g)^2(1+\theta)} f^{"}(\hat{k}) \frac{u'(\hat{c})}{u''(\hat{c})}$$

where g is the population growth rate, and $\hat{k}$ and $\hat{c}$ are steady-state capital and consumption. Mercenier and Michel (1994b) show that their method is superior to Manne's (1992). Using their method will allow us to examine the timing of abatement in the near-term much more closely than with the 10 year periods used by Shiell and Lyssenko (2014).

Mercenier and Michel (1994a) show that a model's steady-state depends on the choice of a specific gridding. They introduce an identity for the discount factor that increases numerical accuracy under time-aggregated approximation (as opposed to continuous time), independent of the spacing chosen:

$$\alpha_{n+1} = \frac{\alpha_n}{1+\theta PT_{n+1}} \qquad n < N, \alpha_0 > 0$$

We take $\alpha_0 = 1$, and the term α_t replaces $1/(1+\theta)^{\Delta t}$ throughout the model.

The model is calibrated and solved for each BAU, which then provides research expenditure levels for the optimal policy with exogenous technology (EXOPT). The endogenous technology optimization (ENOPT) is also run following each BAU so that the α and ρ values used are consistent between the BAU, EXOPT, and ENOPT of each scenario. The second-best policy not is solved. The implied impact of ITC on optimal abatement is calculated using the difference-in-difference metric:

$$\Delta^2 F = \left[\frac{(F_{ENOPT} - F_{BAU})}{(F_{EXOPT} - F_{BAU})} - 1\right] \times 100$$

where F_j is the gross fuel used and emissions in case j = BAU, EXOPT, ENOPT. This metric is an adaptation of Shiell and Lyssenko's (2014) metric, which was based on Popp (2004).

At this time we have been unable to calibrate and solve the model using Gerlagh's (2008) β_t and the period length adjustments described above. We hope to continue working in that direction, but for now present results obtained without shadow value normalization and with 32 periods of 10 years. To avoid terminal value concerns, and because they add little insight, the final 17 periods are not included in the results presented; i.e. results are presented for the first 15 periods only.

Results

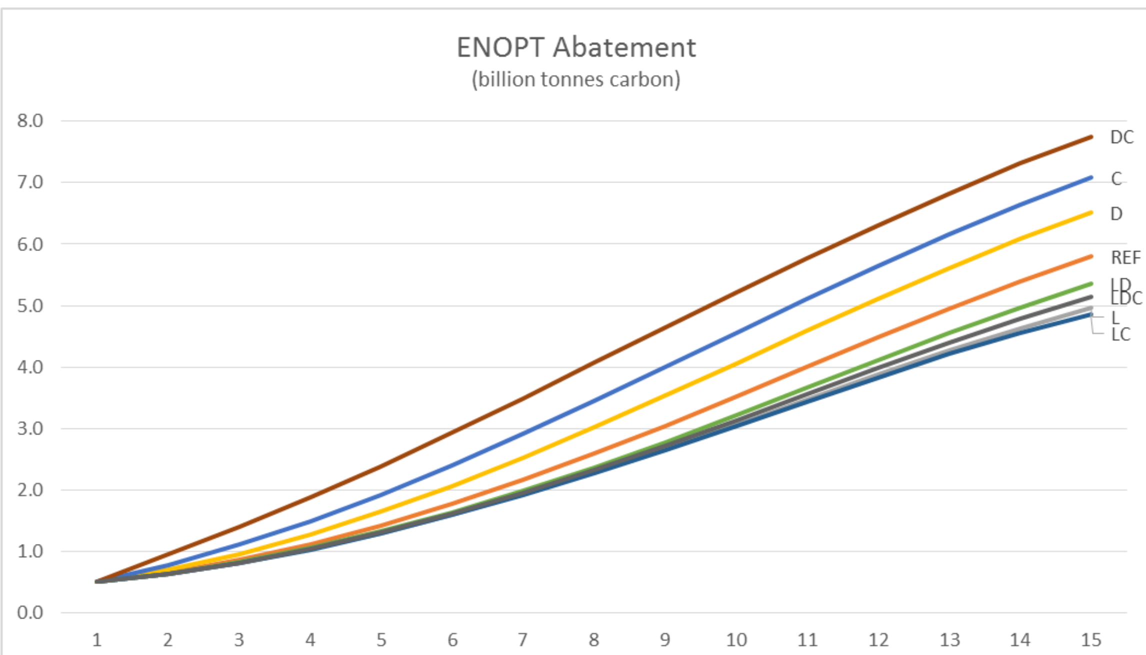

Figure 1. Abatement in first-best with ITC

Figure 1 shows the levels of abatement found by solving the first-best optimal case with each internalization scenario. First period abatement is equivalent across scenarios. Unfortunately, as periods are each 10 years, it is unclear if there are any very-near-term abatement delay implications from this comparison. The abatement in the REF scenario is middle of the pack. All leakage internalizing scenarios being below REF implies that the leakage effect dominates duplication and crowding out, as expected based on $\psi = 2.80$. Duplication scenario abatement is above REF levels. Internalizing inter-firm leakages (duplication or crowding out) in the BAU raises (lowers) the return to R&D in the RA's problem. Thus, when leakages are internalized in the BAU, we see implausibly high levels of R&D in the BAU. It follows that there is less benefit from R&D in the ENOPT case, and we see a lower level of abatement than if leakages had been external in the BAU. On the other hand, when duplication or crowding out is internalized in the BAU, R&D levels in the BAU are implausibly low. Thus, there is greater benefit from R&D in the ENOPT case, and we see higher levels of abatement than if duplication or crowding out had been external in the BAU. We mentioned previously that the optimism of Gerlagh (2008) may be biased because he internalizes duplication in the BAU. The results for scenario D in Figure 2 support our suspicions.

Interestingly, despite crowding out internalization leading to above-REF abatement, it seems to behave more as an amplification for the other externalities than to drive their abatement upwards: LDC below LD, LC below L, and DC above D. In ENOPT $\psi = 2.80$, but it has a different value in some BAU scenarios. For instance, $\psi = 0.7$ for the LC BAU and $\psi = 4.0$ for the DC BAU, while it is 2.80 for the C BAU (Shiell & Lyssenko, 2014). It is inconsequential for BAUs with *crowdout* = 0. Consider the comparison of DC to D: As mentioned above, when duplication is internalized in the BAU R&D levels in the BAU are implausibly low, and we see higher levels of abatement in ENOPT than if duplication had been external in the BAU. However, if crowding out is internalized as well, we move from $\psi = 4.0$ in the BAU to $\psi = 2.80$ in ENOPT. Thus, there is an opportunity cost (benefit) from crowding out when it is internalized along with duplication (leakages). It follows that the understated (overstated) benefit from R&D in the BAU with duplication (leakages) internalized is accentuated by the opportunity benefit (cost) introduced with crowding out.

This basic analysis shows that abatement levels from other models may be heavily influenced by the R&D externalities they internalize in the BAU; however, we see little variation in trends. It is also important to note that this data is not based on ΔF^2 values, but simply $F_{BAU} - F_{ENOPT}$, so the abatement shown is attributable to both the addition of environmental policy and the presence of ETC; i.e. some portion of the abatement also occurs with exogenous technological change.

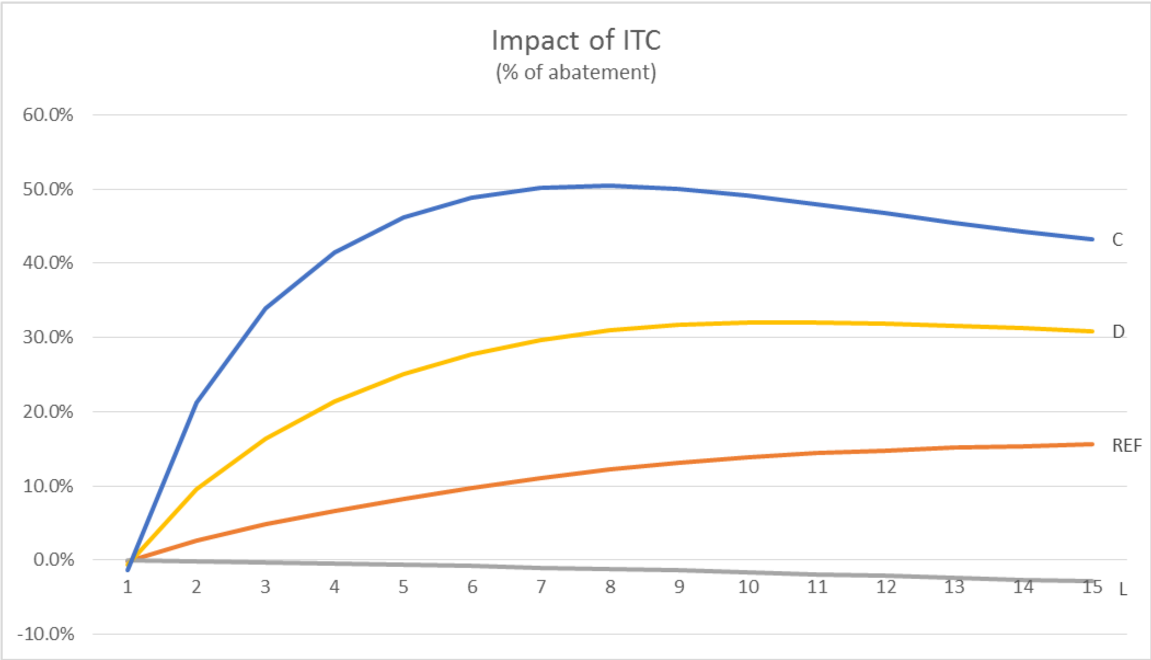

Figure 2. Percent of abatement attributed to ITC (single internalization)

Figure 2 shows the ΔF^2 values for the REF and single internalization scenarios. We see that without any externalities internalized, ITC leads to a modest share of the abatement seen in Figure 1, 10% after 6 periods, and below 20% in the long-term. ITC appears responsible for the greatest share of abatement with crowding out internalized, followed by duplication. Figure 2 supports that when crowding out or duplication are internalized in the BAU, R&D levels are implausibly low and there is greater benefit from R&D in the ENOPT case. Having leakages internalized in the BAU makes ITC appear to slightly reduce abatement (relative to exogenous technology). Because the level of R&D is overstated with leakages internalized in the BAU, R&D (emissions) is lower (higher) in the ENOPT where all externalities are accounted for. In period 1 of the REF scenario ITC lowers abatement by 0.16%. The impact appears more negative with crowding out internalized (-1.35%), and with duplication internalized (-0.62%).

The implied impact of ITC on abatement in the first period is precisely 0 with leakages internalized in the BAU. This is evidence not only that ITC delays abatement, but more importantly that internalizing crowding out and duplication shows greater delay, and leakages less, than the appropriate BAU. Once again, shorter time periods in the near-term would give greater clarity to this discussion.

Figure 3 shows the ΔF^2 values for the multiple internalization scenarios. The impact of leakages is quite clear. All scenarios which internalize leakages show almost no impact of ITC on abatement, timing or scale. Most opportunities to gain from R&D are captured by the RA in LD and LDC because the leakages effect is so strong. There is excessive R&D in the BAU in LC, similarly to L above. Internalizing all three externalities in the BAU leads to the result that ITC has no impact on abatement. This comes as little surprise as the RA has already accounted for all externalities aside from pollution. Crowding out amplifies both the leakage and duplication effects, for reasons discussed above. The DC scenario implies the greatest delay in abatement due to ITC ($\Delta F^2 = 2.60$ in period 1) and in the scale of ITC's impact. This fits with our intuition that internalizing these two externalities in the BAU lowers the R&D value perceived by the RA, and thus there is more to be gained from ITC. In order to pay for the robust levels of ITC in this scenario, it is optimal to abate less in the first period under ENOPT than under the EXOPT scenario.

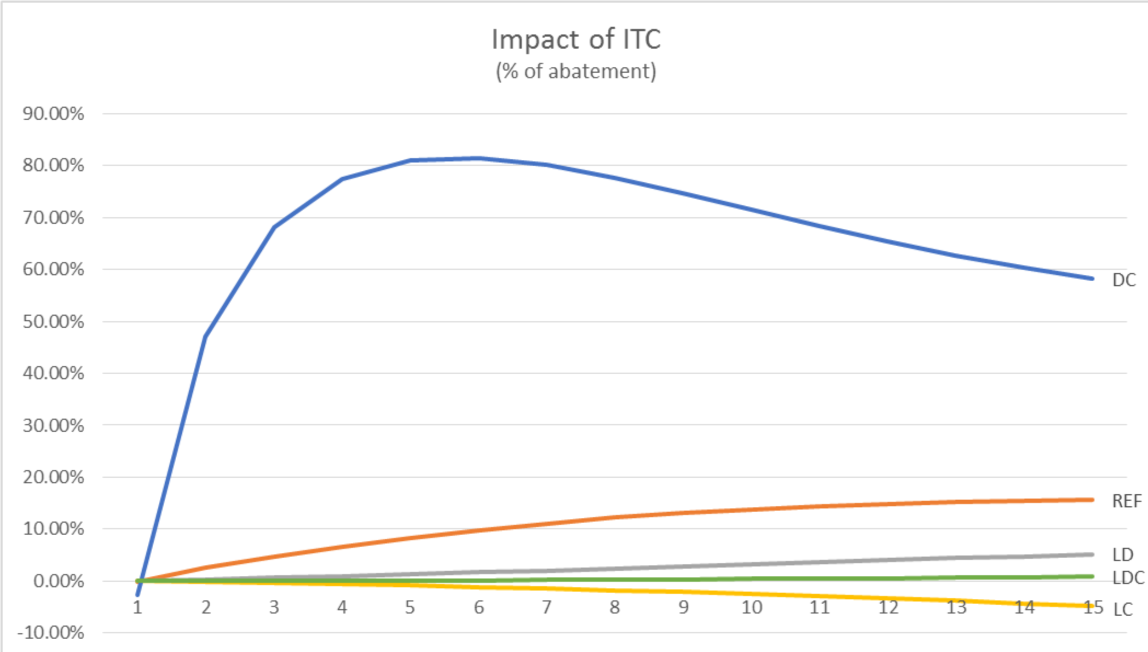

Figure 3. Percent of abatement attributed to ITC (multiple internalizations)

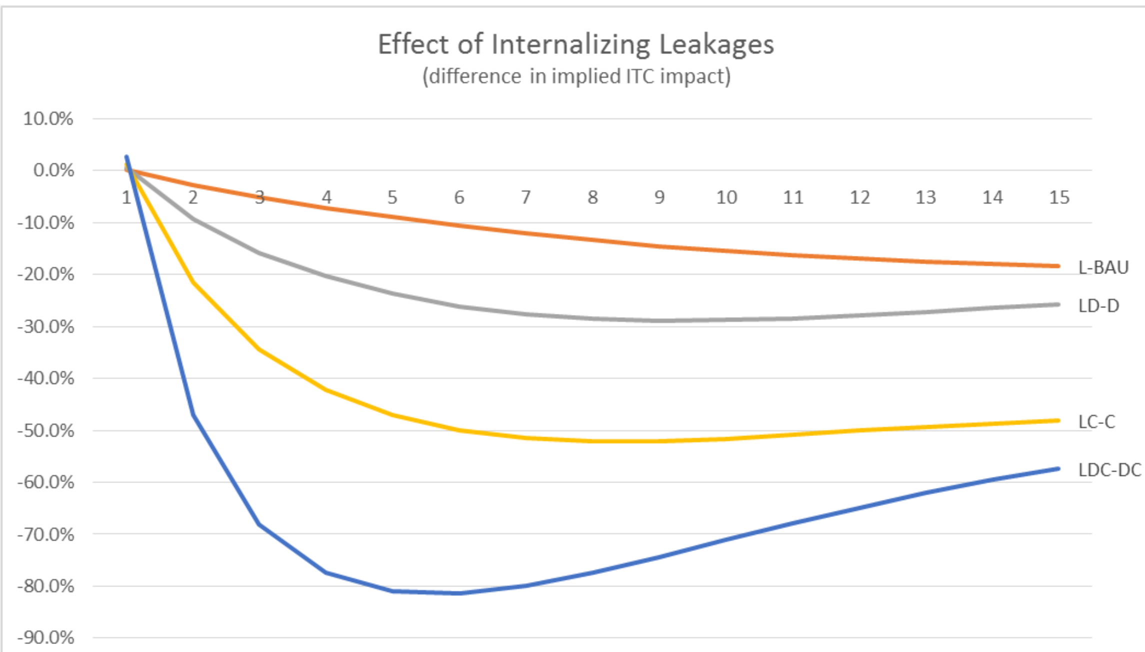

Figure 4. Effect of Internalizing Leakages

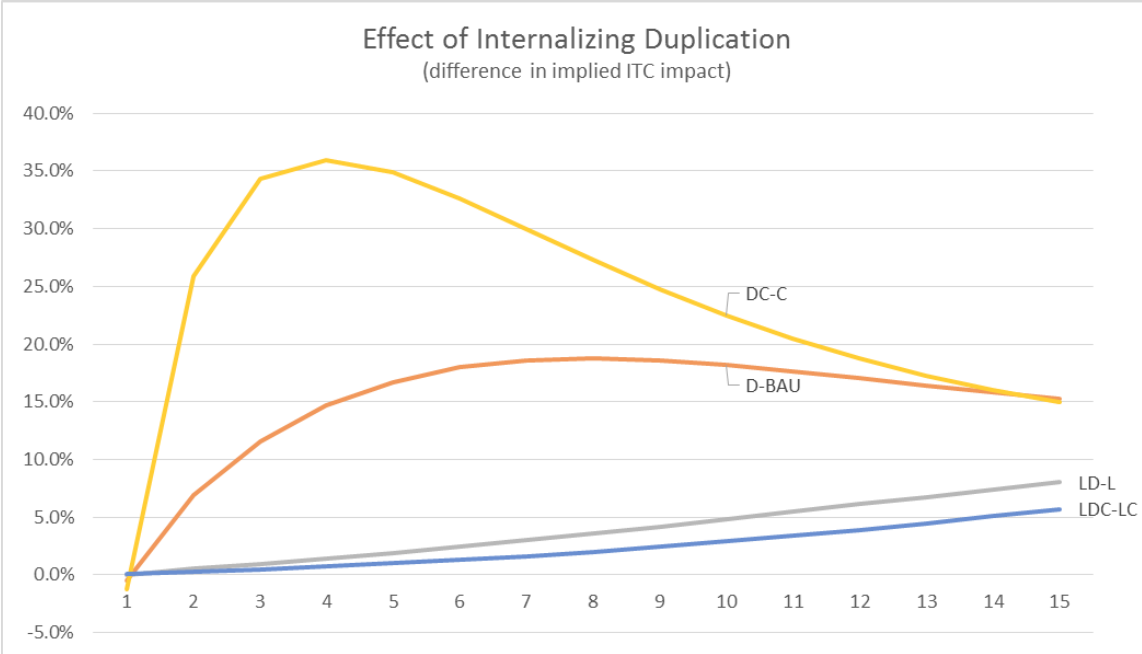

Figure 5. Effect of internalizing duplication

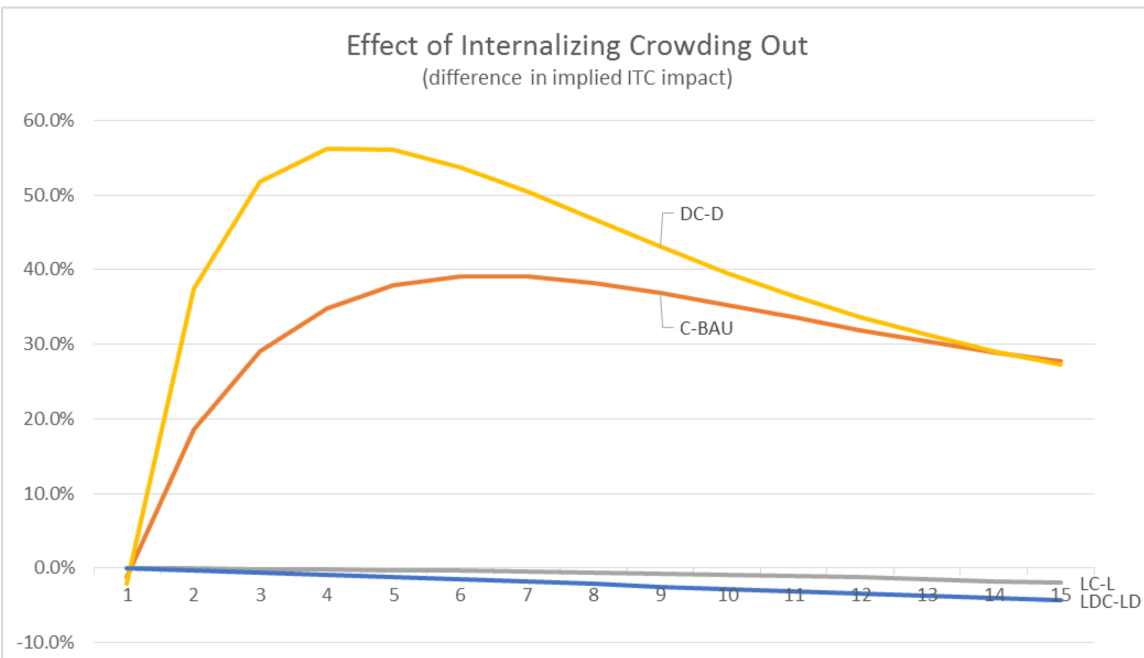

Figure 6. Effect of internalizing crowding out

Figures 4-6 highlight the interactions within each externality combination by subtracting the implied ITC impact of the scenarios without an externality internalized from the scenario gaining only that internalization. For example in Figure 4 we see the label LC-C which indicates the difference in implied ITC impact between the scenario which internalizes both leakages and crowding out in the BAU and the scenario which internalizes only crowding out. This allows us to examine each externality individually as well as visualize the interaction between various externalities. These figures confirm the conclusions obtained above. Internalizing leakages negates the delay of abatement caused by ITC and lowers its implied impact on abatement, we see this in Figures 3 and 4. Duplication has the least impact on ITC because we have chosen b = 0.7 (relatively close to 1). The general trends of duplication and crowding out are the same, but crowding out shows a greater impact. When crowding out and duplication are internalized together in the BAU their impacts are amplified in the earlier periods but over time fall just below the C-BAU and D-BAU curves. This result is somewhat puzzling, and may require some sensitivity analysis to provide greater clarity.

Conclusion

There is little doubt of the importance of climate change. Achieving our climate goals will depend heavily on the development of new technologies, and so the economic modeling community has put forth great effort to incorporate more realistic representations of technological change. ETC can be modeled as learning-by-searching (R&D) or learning-by-doing (LbD). Both contain intertemporal externalities through which past action affects current and future mitigation costs. This paper is concerned with the impact of R&D externalities often included when ETC is built into a model. These externalities should remain external to the representative agent. There are arguments in favour of delay, though that delay truly means near-term investment in R&D. Early policies may be needed so that long-lived capital can be replaced in time to hit targets, without premature retirement. With R&D accumulation there is likely delay in abatement due to ITC; however, the scale of ITC's impact is debated. Optimal carbon taxation is dependent on the relative undersupply of technologies, the externalities incorporated, and whether or not R&D subsidies are available to the social planner.

There is little consistency in the literature for modeling the BAU. While Rezai (2011), Rezai, Foley, and Taylor (2012), and Shiell and Lyssenko (2014) advocate that all externalities be external in the BAU this is often not the case. It is not uncommon to internalize some or all R&D externalities included in the model (Buonanno, Carraro, & Galeotti, 2003; Gerlagh, 2008; Gerlagh, 2009; Grübler & Messner, 1998; Hart, 2008; Jones & Williams, 2000). Internalizing these externalities is likely to bias results on the scale impact of ITC and on the timing of abatement. Shiell and Lyssenko (2014) support Rezai's (2011) contention that externalities should be external in the BAU, and the intergenerational equity concern is a second-order effect. They find that the impact of ITC is highly dependent on the degree of duplication considered. They expect duplication to be low, and given low duplication other externalities are significant and R&D subsidies make first-best policy possible.

We use the model of Shiell and Lyssenko (2014). We aim to incorporate Gerlagh's (2008) price deflator in order to normalize shadow values, and implement varying time periods based upon Mercenier and Michel (1994a, 1994b). Their method equalizes the optimal level of net investments in each period, and will allow us to examine the timing of abatement in the near-term much more closely than with the 10 year periods used by Shiell and Lyssenko (2014). Mercenier and Michel (1994a) introduce an identity for the discount factor which replaces the discount rate throughout the model and allows for time aggregation while maintaining the same steady-state. The model is calibrated and solved for each BAU, which then provides research levels for the exogenous technology optimization (EXOPT). The endogenous technology optimization (ENOPT) is also run following each BAU so that the α and ρ values used are consistent between all three cases of each scenario. The impact of internalizing a given (set of) externalities on the implied effect of ITC is calculated using a difference-in-difference metric using emission levels.

First period abatement is equivalent across scenarios. Unfortunately, as variable period lengths have not yet been implemented, in the result shown it is unclear if there are any very-near-term abatement delay implications. The leakage effect dominates duplication and crowding out (with our parameters), as expected based on $\psi = 2.80$. Crowding out amplifies the other externalities. Without any externalities internalized, ITC leads to a modest share of the abatement seen in Figure 1, 10% after 6 years, and below 20% in the long-term. ITC appears responsible for the greatest share of abatement with crowding out internalized, followed by duplication. Having leakages internalized in the BAU actually makes ITC appear to slightly reduce abatement (relative to exogenous technology). In period 1 we see that abatement is lowered by ITC. This is evidence not only that ITC delays abatement, but more importantly that internalizing crowding out and duplication shows greater delay, and leakages less, than the appropriate, all-external case. Internalizing all three externalities in the BAU leads to the result that ITC has no impact on abatement, despite showing a lower level of total abatement in Figure 1 (ITC and pollution policy). Internalizing leakages negates the delay of abatement caused by ITC and lowers its implied impact on abatement.

We have shown that internalizing R&D externalities in the BAU will bias the implied impact of ITC. Future examinations of ITC and the timing of abatement should adopt a more consistent method of solving the RA's problem. It will be informative to perform a sensitivity analysis of the externality parameters; furthermore, we hope to collect results with shorter near-term period lengths.

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